Methods and observations in microfabricated ion trap arrays

M. J. Curtis, G.Imreh, J.P.Home, B.C.Keitch, A. H. Myerson, E. Phillips, J. A. Sherman,
D.J. Szwer, N.R.Thomas, S. C. Webster, D.N.Stacey, D.M.Lucas and A.M.Steane
Centre for Quantum Computation, Clarendon Laboratory, Oxford University, U.K.

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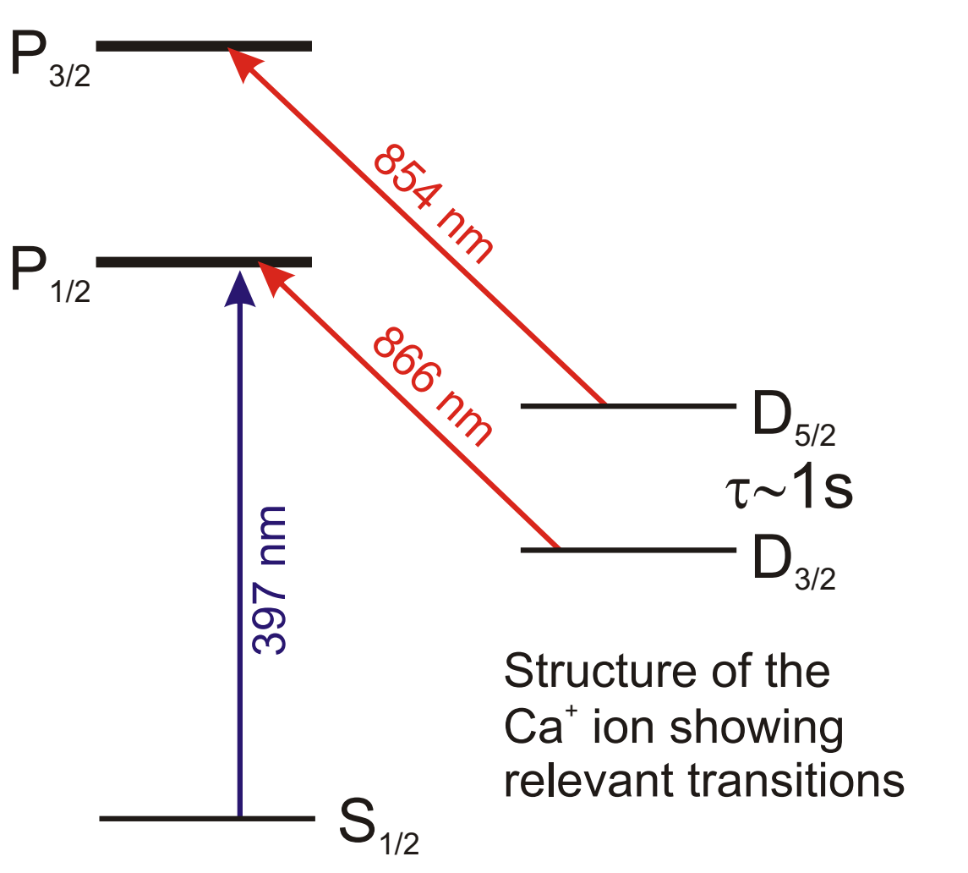
Main points

We present experimental design issues in setting up a new ion trap experiment based on a microfabricated trap array packaged on a chip carrier.

We describe simulation studies of the array, and experimental observations using $^{40}Ca^+$ ions.

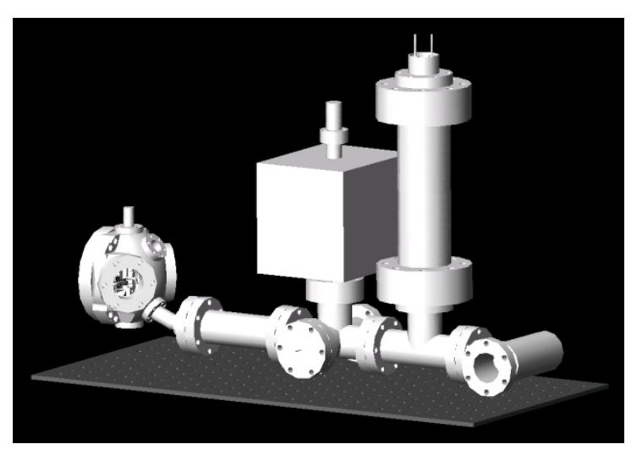


Structure of the Ca^+ ion showing relevant transitions

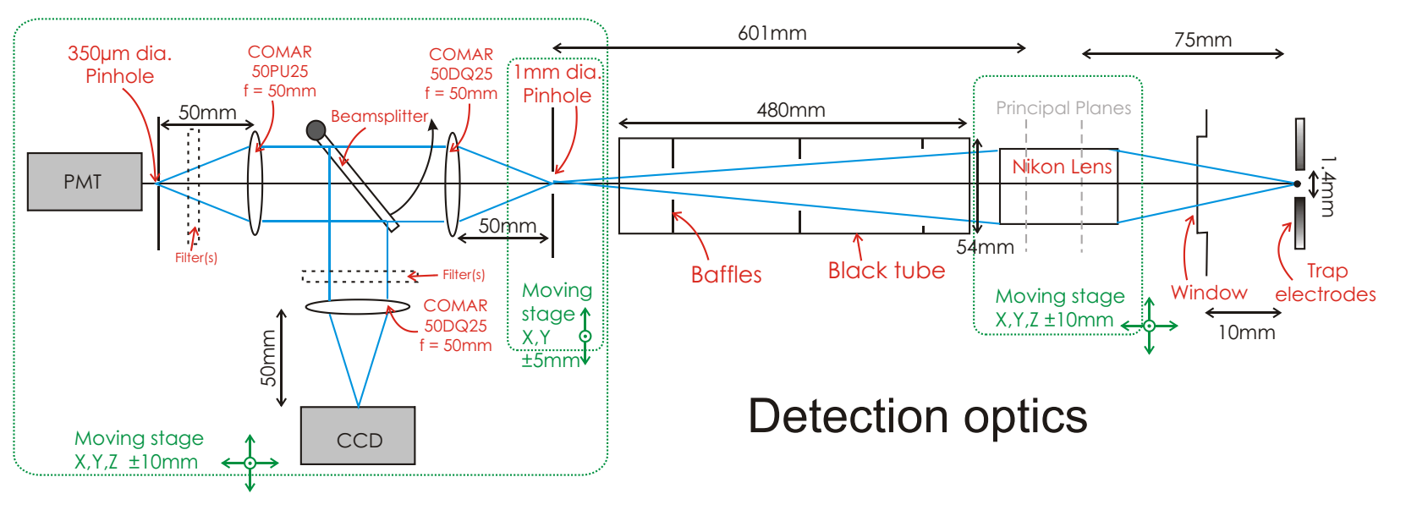
Summary of Results

- ♦construction of vacuum-compatible chip socket, as designed by Univ. Michigan ion trap group
- ♦modification of the socket and the electrode structure
- ♦systematic and automatized analysis of electric potential
- ♦installation, baking and loading of ion trap. Base pressure ~1 x 10^{-10} mbar.
- ♦trap lifetime 1s without laser cooling, 1 hour with laser cooling.
- ♦secular frequencies approximately as expected
- ♦ion heating rate measured by Doppler cooling/fluorescence method. Value: 70 K/s, i.e. high!

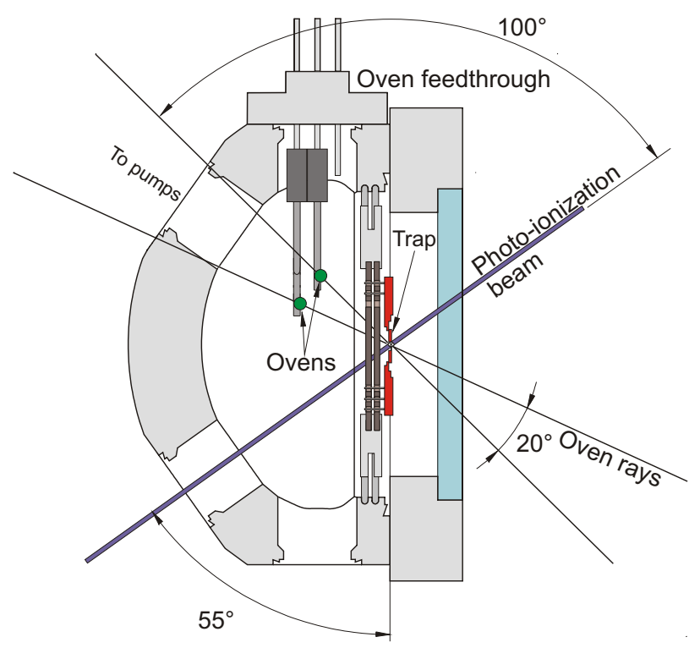
Setting up the new system



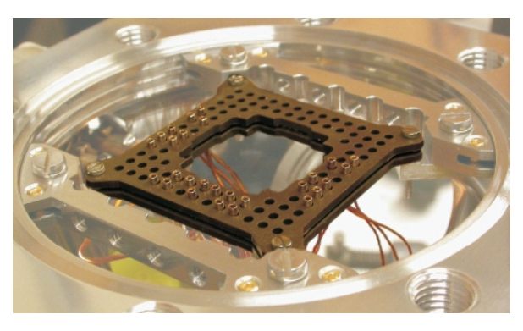
Vacuum system overview



Detection optics

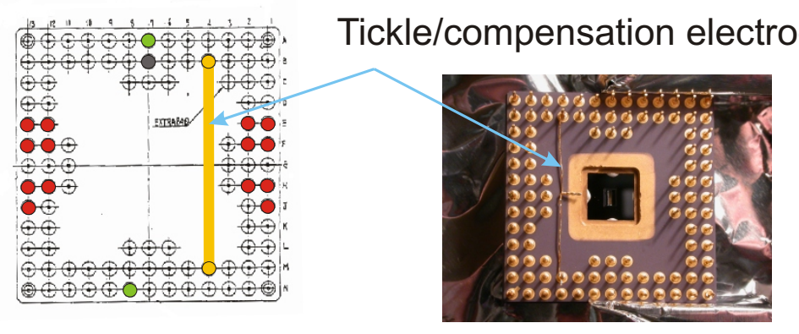


Section showing geometry for photoionisation loading

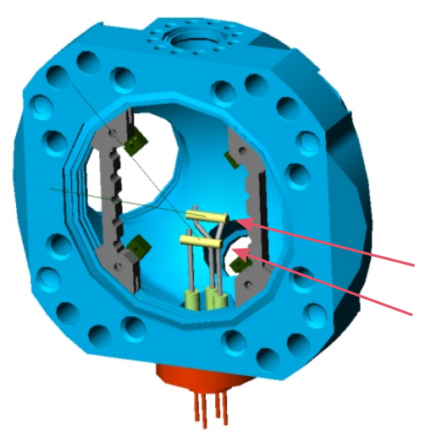


Completed socket for Kyocera package mounted in vacuum hemisphere

Installing extra electrode for compensation and "tickling"



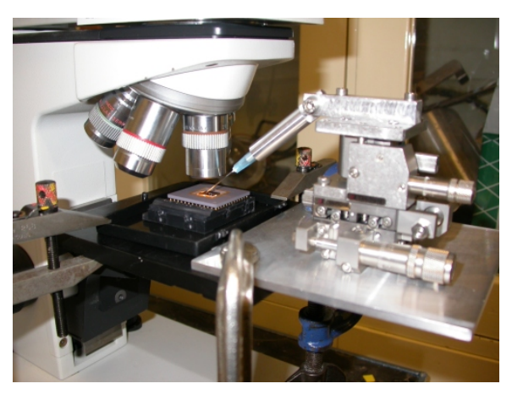
Wire Used:
Goodfellow Cambridge Limited
LS309119 J V AU005140/30
Diameter: 0.25mm
High Purity: 99.99%
Temper: Hard



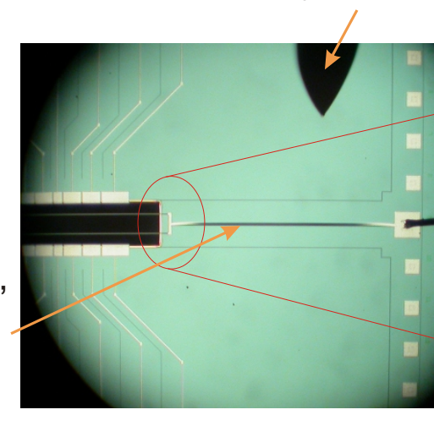
Mounting of dual ovens

Ca43 enriched
Natural abundance

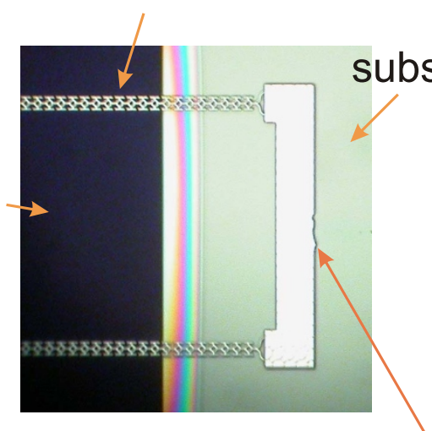
Removal of unwanted r.f. connection



Preparing to do the "cut": microscope and needle translation stage

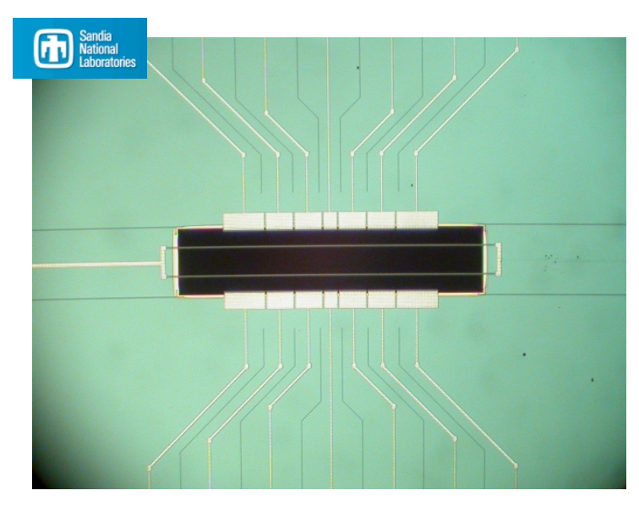


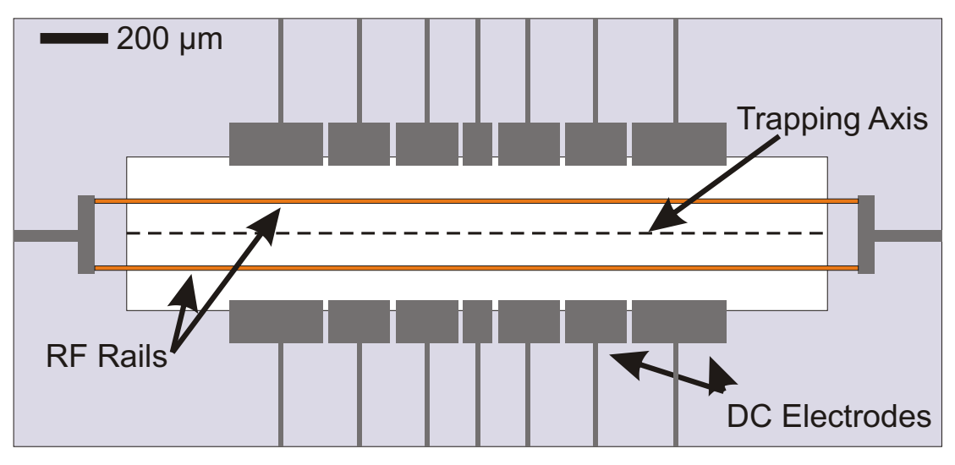
View through optical microscope



The result: a clean break (by work hardening?)

D.C. Voltage setup





DTO module 4 trap, designed and fabricated by Sandia National Laboratoies, Albuquerque, New Mexico (Matt Blain).
Materials: tungsten on silicon, with gold coat on backplane,
1 r.f. electrode pair and 14 d.c. electrodes around a 2mm x 0.4mm vacuum slot.
Ion to electrode distance $\rho_0 = 99.5$ µm.

Finding the required electrode voltages:
1. Pick desired trap centre location (or locations) ***c***
2. Calculate the potential near ***c*** for each electrode in turn, i.e. chosen electrode at ϕ_i=1 Volt, all others grounded, and fit by Taylor expansion:

$$V_i = \phi_i[\alpha_{xi}(x-x_i)^2 + \alpha_{yi}(y-y_i)^2 + \alpha_{zi}(z-z_i)^2 + C_i]$$

3. A voltage set $\{\phi_i\}$ will result in a potential well centred at

$$x_\Sigma = \frac{1}{\alpha_\Sigma}\sum_{i=1}^{n}\phi_i\alpha_i x_i$$

With quadratic coefficient (sets the trap tightness):

$$\alpha_\Sigma = \sum_{i=1}^{n}\phi_i\alpha_i$$

4. Choose target values. For example: $\alpha_{z\Sigma} = Q_{dc}, \ \alpha_{y\Sigma} = \alpha_{x\Sigma} = -\frac{Q_{dc}}{2}$

$$x_\Sigma = y_\Sigma = z_\Sigma = 0$$

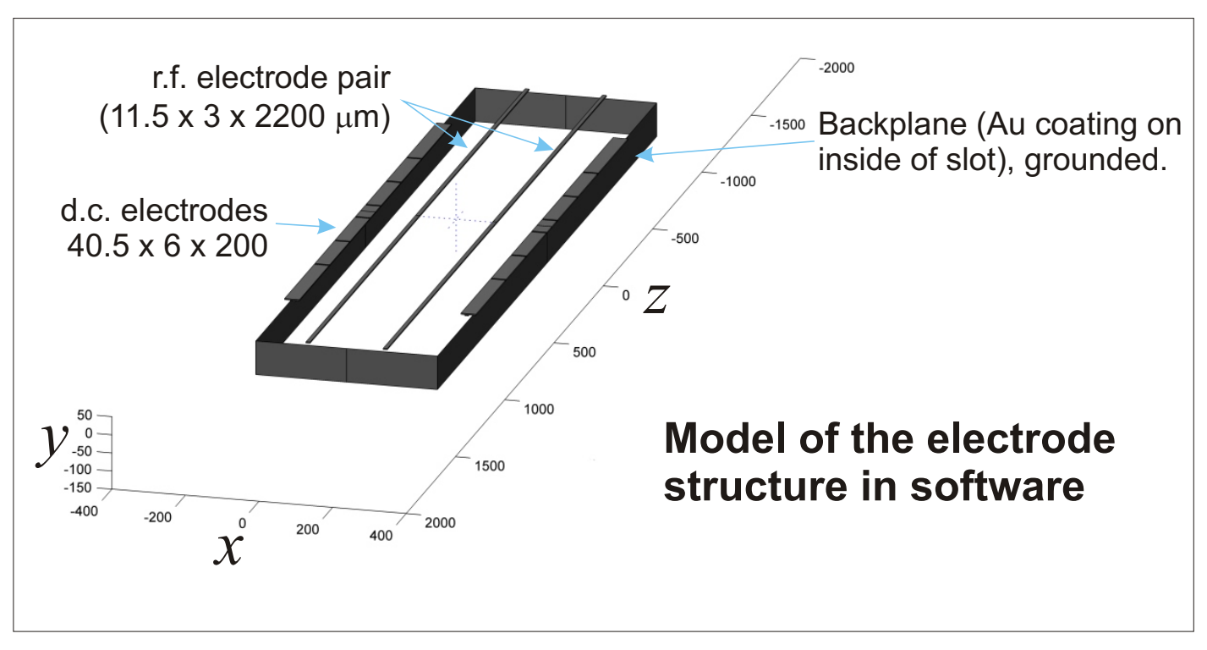
5. Obtain required $\{\phi_i\}$ by solving the linear system:

$$\sum_i \phi_i\alpha_{zi} = Q_{dc}$$
$$\sum_i \phi_i\alpha_{xi} = -\frac{Q_{dc}}{2}$$
$$\sum_i \phi_i\alpha_{xi}x_i = 0$$
$$\sum_i \phi_i\alpha_{yi}y_i = 0$$
$$\sum_i \phi_i\alpha_{zi}z_i = 0$$

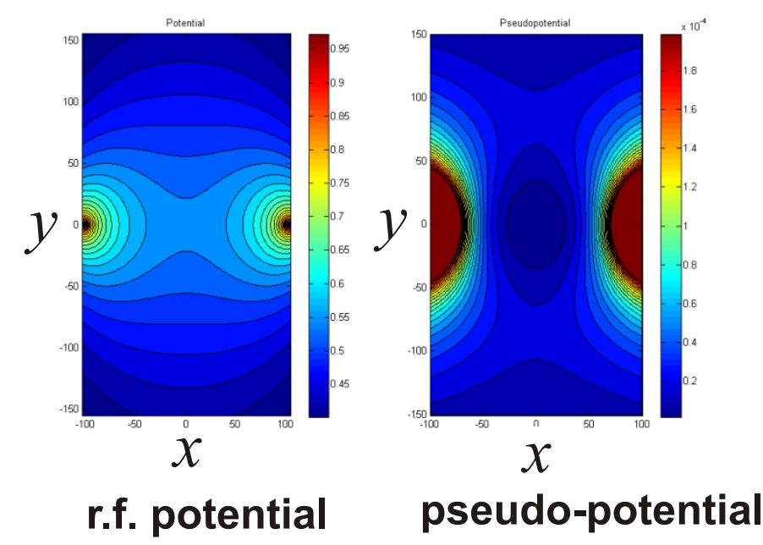
6. Voltage adjustments for stray field compensation found by similar procedure.

Electric potential calculations

Numerical solution of Laplace equation by boundary element method, using *CPO.*

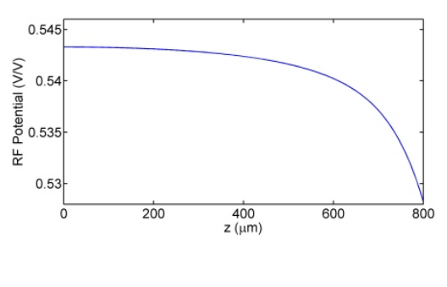


Model of the electrode structure in software

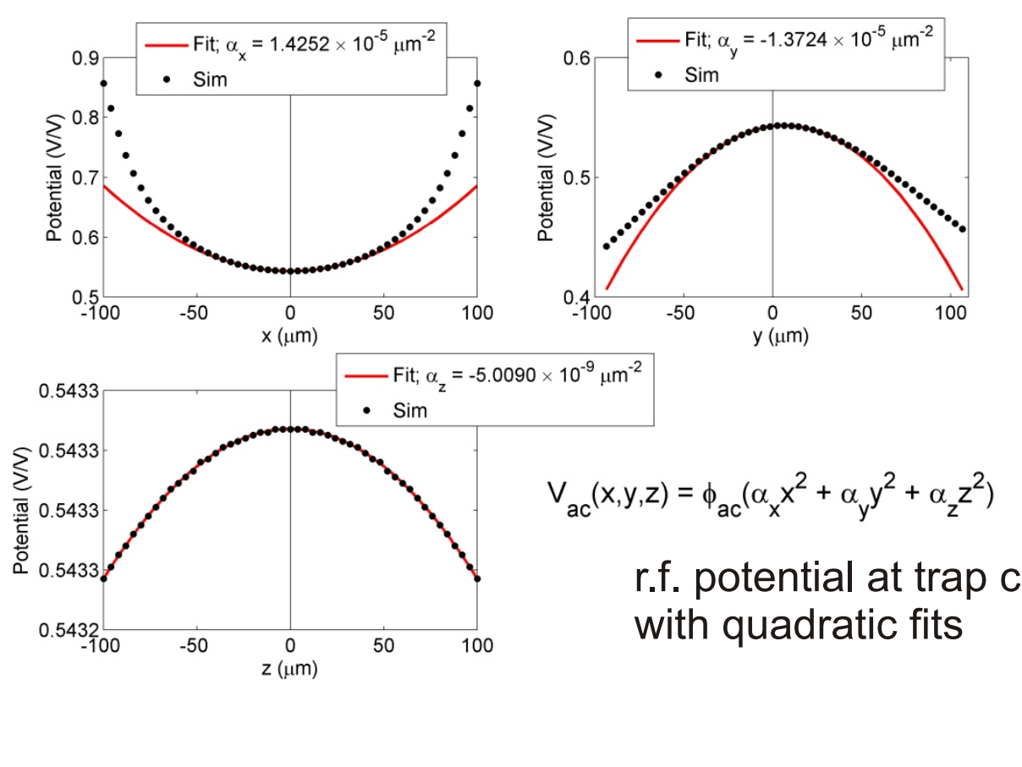


r.f. potential at t=0

pseudo-potential

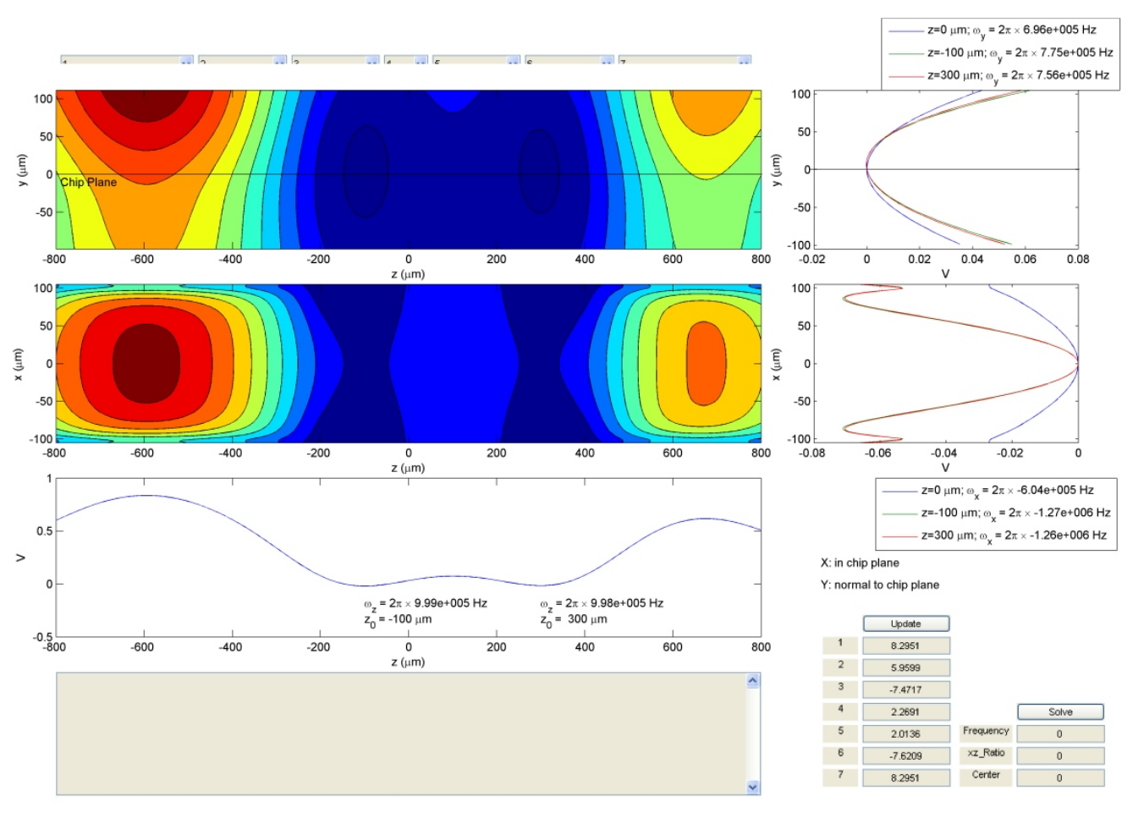


r.f. potential along trapping axis (no r.f. bumps)

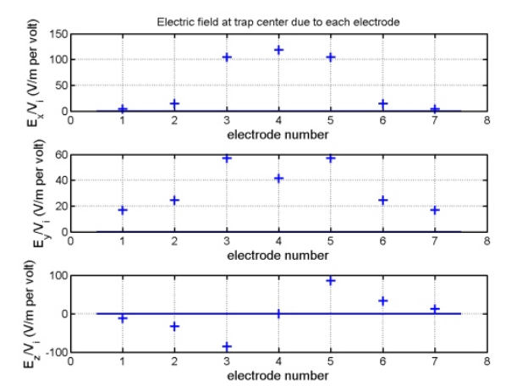


$V_{ac}(x,y,z) = \phi_{ac}(\alpha_x x^2 + \alpha_y y^2 + \alpha_z z^2)$

r.f. potential at trap centre with quadratic fits



Example d.c. solution for trap centres at -100 µm, 300 µm with ν_z = 1 MHz



Electric field at trap centre from each electrode. The backplane electrode breaks the vertical symmetry, allowing stray field compensation in all directions.

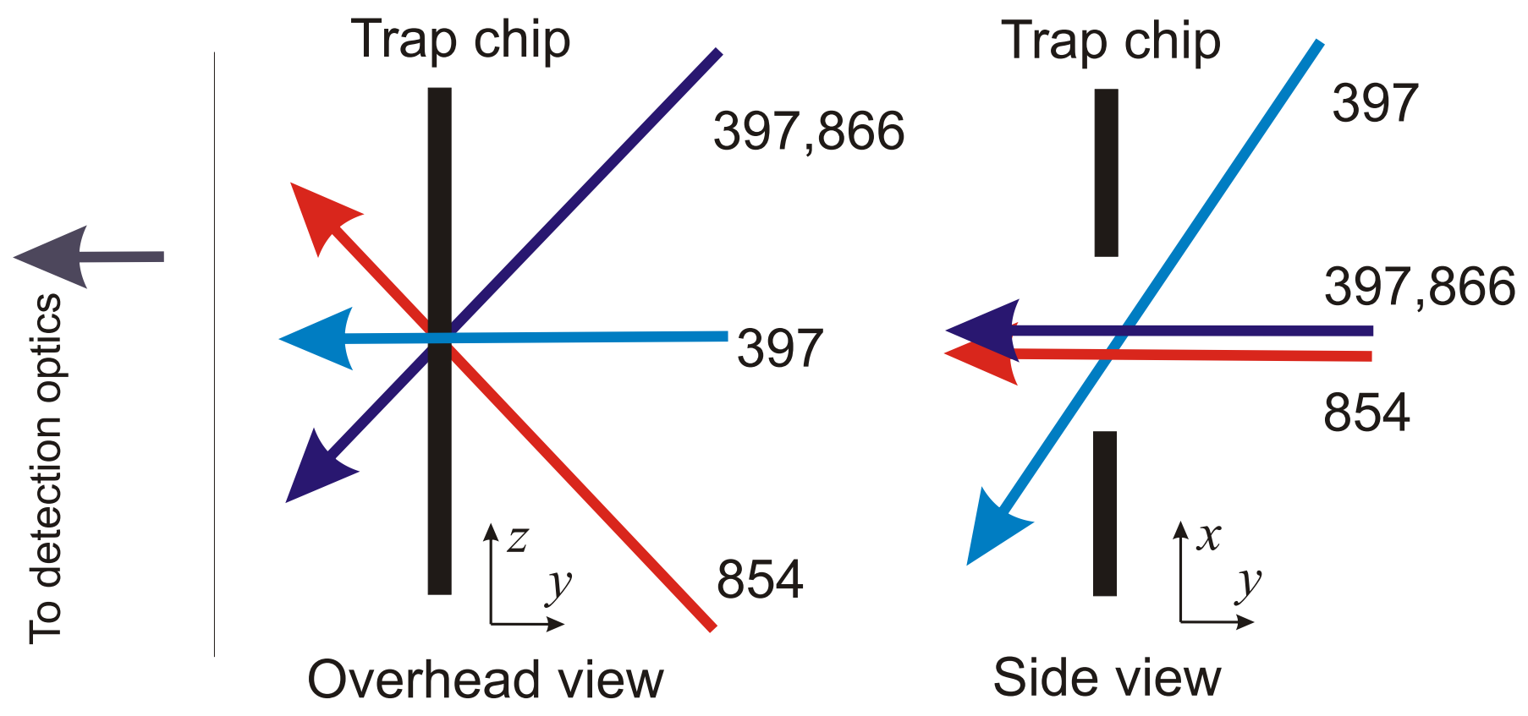
Geometric coefficients (Home, and A. M. Steane, Quantum Information and Computation, Vol. 6, No 4&5 (2006) 289-325.)

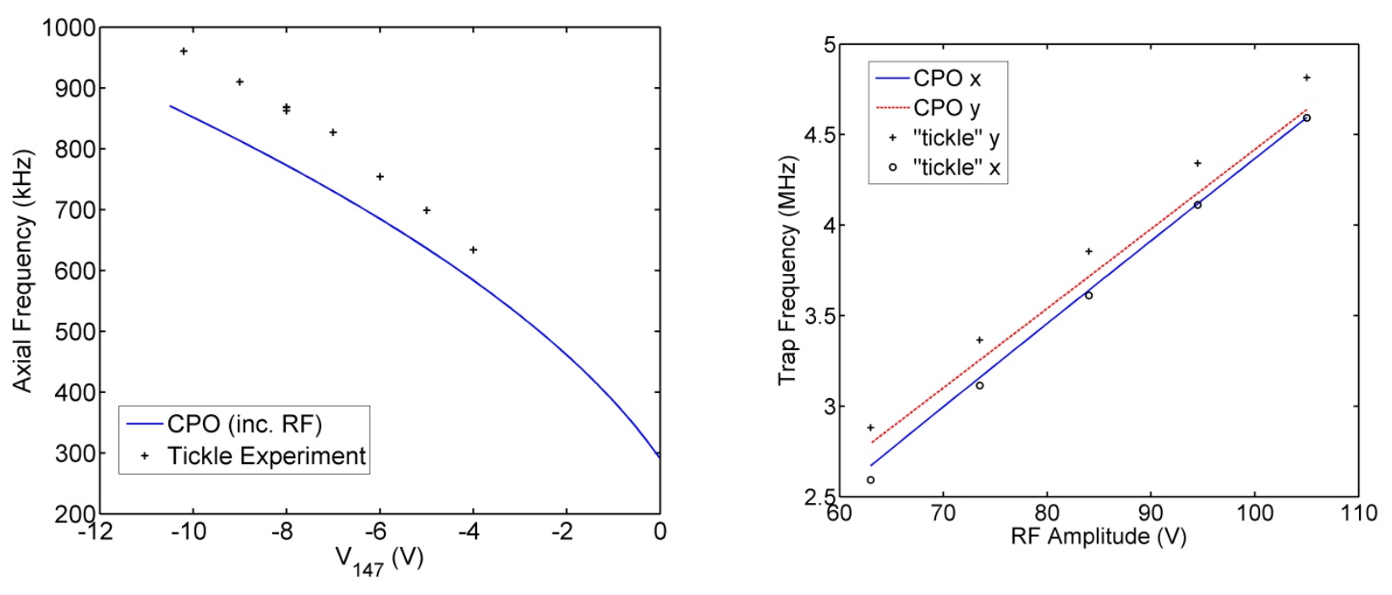
$$\text{r.f. quadrupole coeff.} \quad \mu \equiv \frac{\rho_0 Q_{ac}}{E_{\max}} \simeq 0.02$$

$$\text{d.c. octopole coeff.} \quad \gamma_4 \equiv \frac{\rho_0^3\beta_4}{E_{\max}} \simeq 5\times10^{-5}$$

Experimental observations

Laser beam directions at the trap

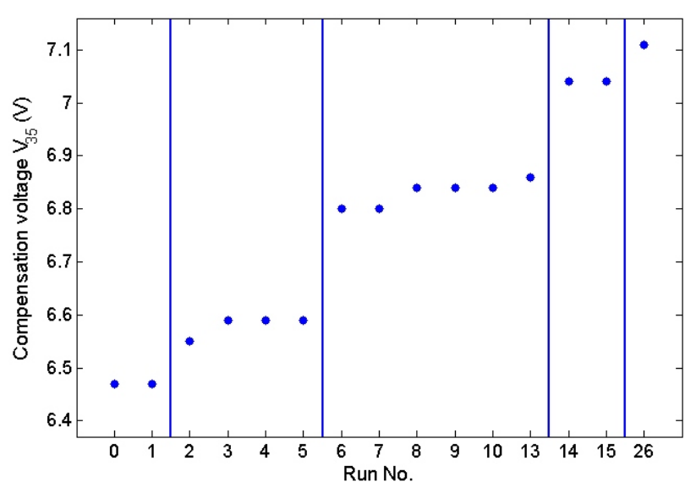




Axial (left) and radial (right) secular frequencies, measured by 'tickling' (data points), compared with predictions from the CPO numerical model (lines).
With no free parameters for the axial case, we see reasonable but not precise agreement. In the radial case we adjust the r.f. amplitude to fit the data (r.f. freq = 27.25 Mhz, 190V pk-pk for ν_x=4 MHz) and again get reasonable but not precise agreement. The discrepancy cannot be removed by slight adjustments to the geometry.

General observations
Ca40 ions loaded by photoionisation. Background pressure 1x10^{-10} mbar. Doppler cooling and fluorescence from co-propagating 397 nm & 866 nm laser beams, waist = 25 x 85 µm, 50 x 50 µm. RC filters outside the vacuum (R-1.8 kΩ, C=0.1 µF).

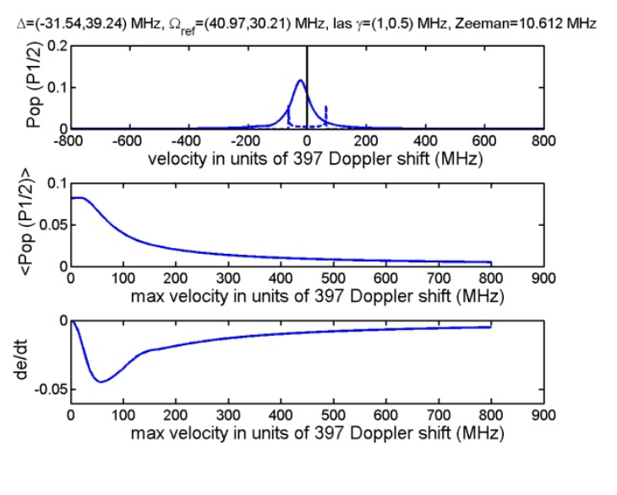
Initially we experienced difficulty loading the trap. This was owing to too high oven current (resulting in fast collisional loss), imperfect setting of the electrode voltages (resulting in lower trap depth), and switching of 866 laser (reducing the laser cooling). Subsequently trap lifetime was of order seconds even with laser cooling, but is now of order hours. However, lifetime without laser cooling remains seconds.



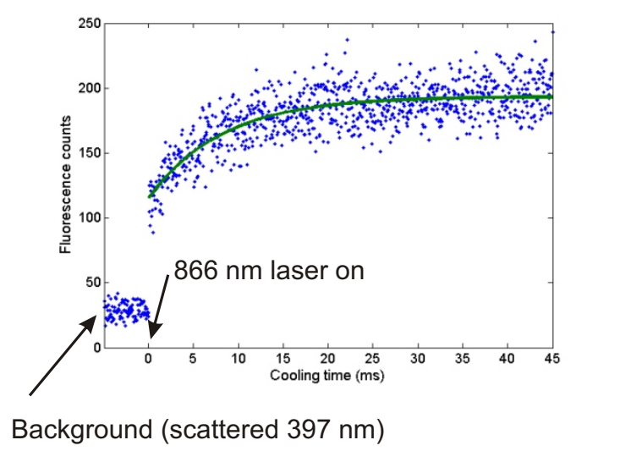
Drift of stray field over several hours (deduced from compensation voltages adjusted by r.f. correlation method). The field changes by approx 10 V/m in 10 minutes. It changes by ~50 V/m when the oven is fired to load a new ion.

Heating rate

Heating rate measured by 'heat and re-cool' method, observing the fluorescence during Doppler cooling. This is sensitive to temperatures O(1 to 100)K, i.e. far from trap ground state (a 1 MHz trap has 50 µK level spacing), but ion orbit is still small and the heating rate near ground state is expected to be similar.

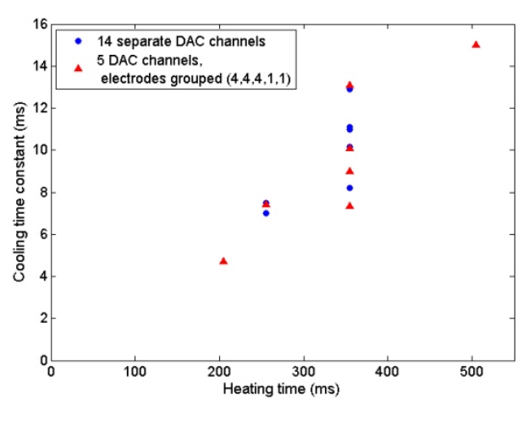


Theory: use optical Bloch equations (8-level SPD manifold in Ca40) to obtain expected scattering rate vs. ion velocity, and hence <dE/dt> averaged over a cycle of simple harmonic motion. This is then averaged for a thermal state, and hence the evolution during Doppler cooling is obtained. Motion is assumed thermalized over 3 dimensions, but micro-motion is not accounted for.



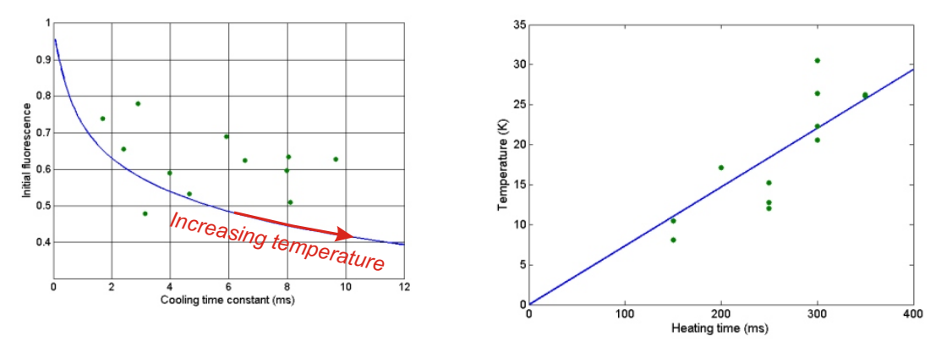
Background (scattered 397 nm)

Example data. Cooling laser beams are suppressed for a period (0.1 to 1s), then reintroduced and the fluorescence monitored. This is repeated 200 to 500 times to accumulate statistics. The data is well fitted by an exponential curve (as expected for a thermal motional state).



Test for electric field noise introduced by the DACs.

●: 14 electrodes driven independently by 14 DACs;
▲: driven in groups by 5 DACs, allowing common-mode rejection. No significant reduction in heating rate, implies heating is mostly intrinsic.

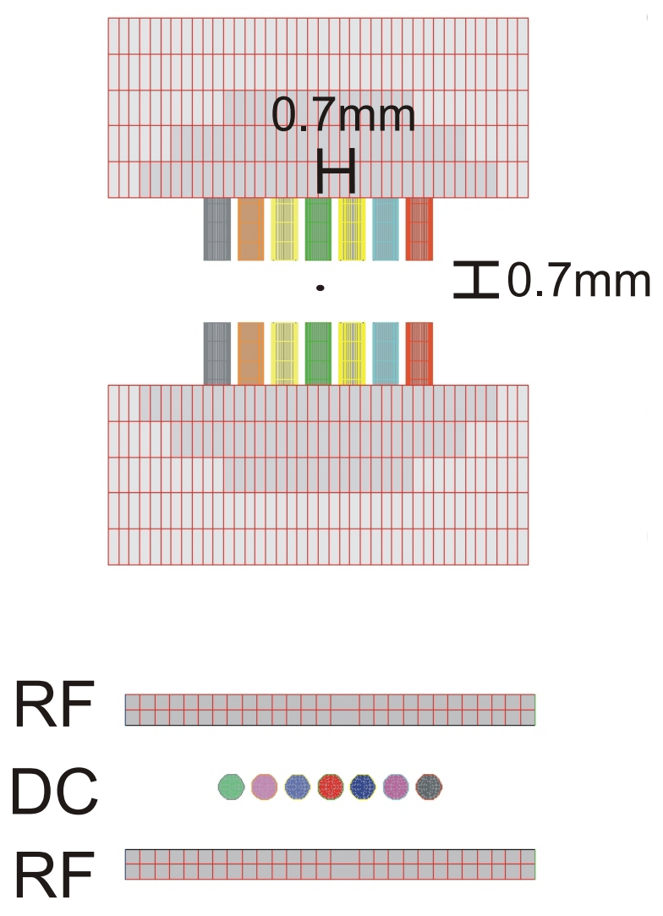


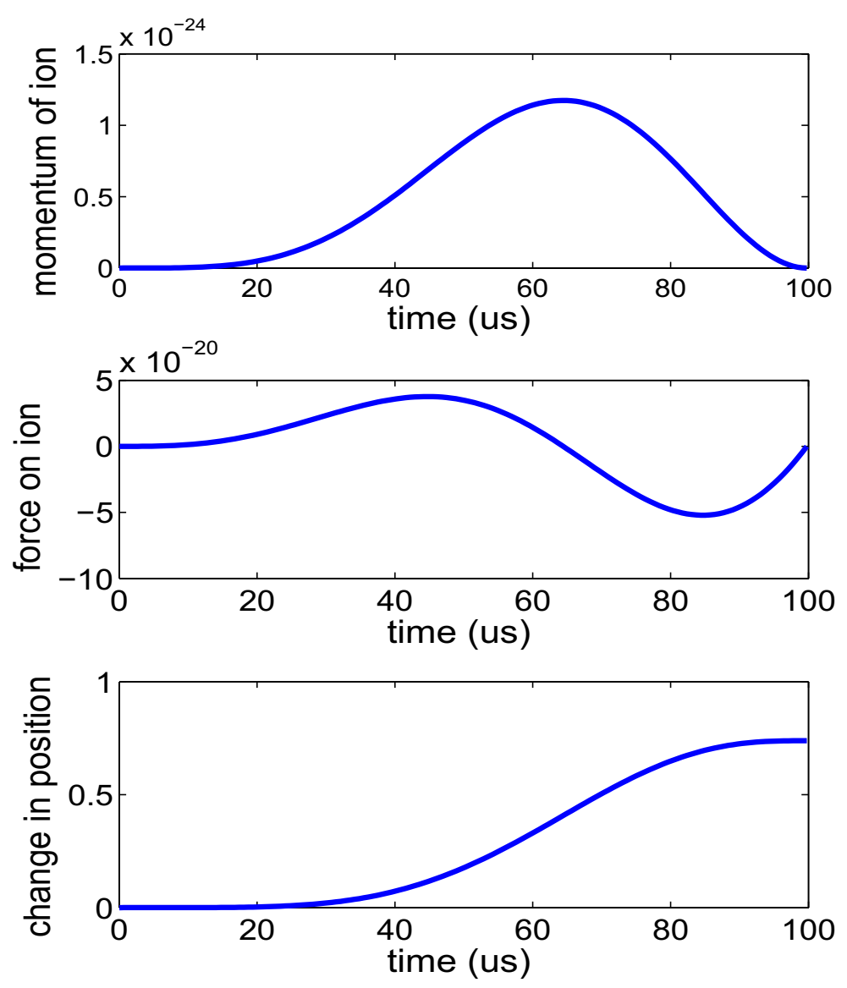
Interpreted data set. The initial fluorescence rate and cooling time constant are only approximately consistent with one another. The latter is more well-behaved, and implies a heating rate ~70 K/s. This is very high compared to other traps of similar dimensions.

Next steps: further trap, shuttling ions

Macroscopic trap to study ion separation and movement:

- 7 pairs of DC electrodes, 4 RF electrodes
- Up to 3 separate trapping regions along the trap axis.
- Operating voltages RF: 1kV @ 10 MHz, DC 25 V
- Status: in vacuum, baking soon

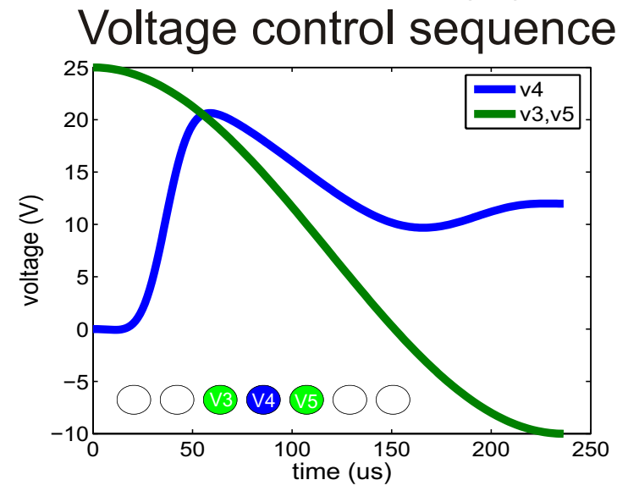


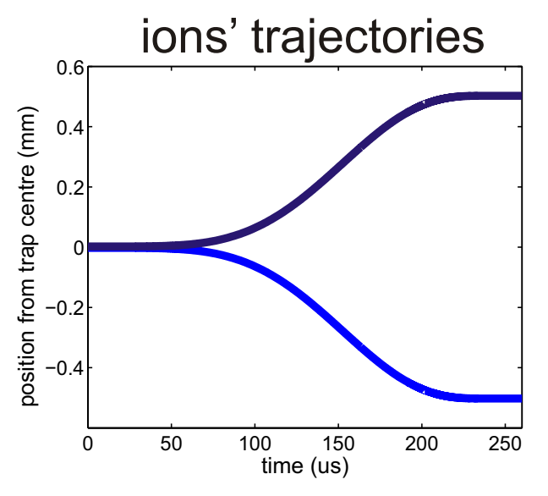


Moving an ion

Deriving the voltage control sequence:
1 Choose a target function for the momentum of the ion as function of time. This dictates the displacement $z(t)$ of the ion and the required force $f(t,z(t))$.
2 Using prior simulations in CPO, deduce the voltages required to produce $f(t,z(t))$.
3 Verify the control sequence by obtaining the ion's motion by numerical integration, and test for sensitivity to imprecision..

Separating ions





Example: splitting a pair at trap centre, where symmetries reduce the calculation to a one-body problem.